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4 ω Thomson scattering probe for high-density measurements at Titan

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In preparation for upcoming experiments on the Titan laser at the Jupiter Laser Facility a new Thomson scattering system has been designed. This system will allow electron temperature and density measures in a high-density regime ($n_e > 10^{21} \text{ cm}^{-3}$) previously inaccessible to Thomson scattering. A 263 nm probe has been designed to produce a total energy of 40 J at 4 ω (263 nm) in a 1 ns square pulse with a focal spot size of 100 μm . This probe will be used for imaging Thomson scattering from thermal electron-plasma waves which will allow the first spatially resolved Thomson scattering measurement of the electron densities above $4 \times 10^{21} \text{ cm}^{-3}$ and will be used to investigate the thermal transport behind the critical surface of a plasma generated by a 1054 nm high-power laser beam.

I. Introduction

Thomson scattering¹ has demonstrated its utility as a valuable diagnostics for understanding the physics of plasmas. This technique provides a non-invasive way to measure bulk plasma parameters such as electron and ion temperature, electron density, plasma flow, and ionization state.²⁻⁵ In addition to measuring plasma properties, Thomson scattering can be used to measure driven electrostatic plasma wave, often as a result of an instability.⁶⁻¹⁰ These measurements are both spatially and temporally resolve by imaging the scattered light in space with a gated measurement or recording the time dependent scattering light from a small region in space.^{4,11} The reason Thomson scattering is such a powerful technique is its versatility and ability to be used with many different experimental platforms especially for high energy density laboratory plasmas, i.e. hohlraums,^{12,13} laser produced plasma foils, gasjets,¹⁴ etc. For these reasons, development of Thomson scattering diagnostics is an asset to laser facilities.

One scientific problem in plasma physics for which Thomson scattering can provide important details is electron heat conduction in laser-produced plasma.¹⁵ In laser-produced plasmas, the bulk of the laser light is absorbed at the cutoff (critical) surface where the plasma frequency matches the laser light frequency. The absorbed energy is then transported primarily by the electron into both the over- and under-dense plasma regions. Due to the sharp gradients in temperature, the heat flux is typically not given by the Spitzer conductivity, $Q = \kappa \nabla T_e$ where T_e is the electron temperature and κ is the conductivity co-efficient. Thus, understanding the heat transport requires measurements of the evolution of the electron temperature, both in space and time. Such measurements can provide details which can be compared with models, as well as Fokker-Planck simulations.

For this application, the forth harmonic, 4ω , of 1 micron laser light from either Nd:YAG or Nd:YLF lasers is the best choice. Higher laser frequencies enable measurements to higher plasma densities. In which case, the heat flow due to the absorption of 1ω light at the critical

surface can be measured in both the over- and under-dense regions. In addition, 4ω Thomson scattering has other advantages such as reduced background due to plasma emission and less dispersion of the probe laser light in the plasma.

In this manuscript, we describe a setup for 4ω Thomson scattering system used to measure electron heat conduction in gradient dominated plasma at the Titan laser facility. The 4ω probe enables measurements at higher plasma densities to investigate electron heat flow into the target from lower frequency heater beam. The goal for the Thomson scattering system was to achieve 10s of Joules of energy to not only measure the ion acoustic waves, but the electron plasma waves which scatter much less laser power.

II. 4ω Thomson scattering probe

The Titan laser facility is a two beam laser facility with both a single short pulse and a long pulse nanosecond beam. Since the electron heat conduction experiment that the 4ω probe is designed for required a long pulse plasma formation beam, a short pulse heater beam, and a 4ω Thomson scattering probe beam, the Thomson scattering beam was formed using light from the long pulse beam. Taking advantage of the facility arrangement, the 1ω leak through light from a 2ω turning mirror in the long pulse beam line was used for the Thomson scattering probe. The 2ω turning mirror used is the last mirror before the light is directed into the rotatable beam tube used to transport the long pulse beam into the target chamber. Using this configuration provides over 100 Js of 1ω light while maintaining ~ 150 J in the 2ω long pulse beam with a 1 ns pulse. The 1ω light can also be boosted by detuning the long pulse conversion crystal at the price of sacrificing the 2ω energy. The 1ω pass through light is then directed through a type II KDP crystal, 18 mm thick, to convert the light to 2ω as shown in Figure 1. The light is then down collimated using a telescope to reduce the beam from ~ 150 mm to ~ 84 mm. The beam is then directed down a periscope to get it to the center line for the target chamber.

Prior to entering the chamber, the light passes through a type I KDP crystal, 6 mm thick, to convert the light to 4ω . Once the 4ω light passes into the chamber, a 6" diameter wedge picks off a small portion of the beam's energy and directs it to the diagnostics. The remainder of the light is focused with a 4" diameter $f/5$ singlet. The probe light is then directed through another 4" diameter $f/5$ singlet to focus the beam. A 2" diameter dielectric mirror is used to reflect the 4ω light into a molelectron calorimeter. The light is filtered using UG5 to pass the 4ω and block the 2ω . The 2ω light passes through the 265nm dielectric mirror and is recorded by a second molelectron calorimeter. The diagnostic beam lines were calibrated using a coherent xxx laser at 532 nm and then at 265nm, through conversion by the crystal, by taking measurements just inside the target chamber and then at the position of the molelectron calorimeters.

One limitation of this setup is the inter beam timing between the plasma formation and Thomson scattering probe beams. The 2ω plasma formation beamline at Titan is contained within a beam tube, and limits the timing between the two beams. To this end, it is possible to move the 4ω beam line up to 2.9 ns before the 2ω beam line and it is easy to have the beam come up to 10s of ns after the 2ω beam.

III. 4ω Crystal Tuning

Initial attempts at tuning the crystal used Titan's regenerative amplifier with a Photomultiplier tube (PMT) at target chamber center. The PMT was filtered with 3 mm UG-5 to eliminate the 2ω light. However, the full aperture beam did not have enough power to convert the light to 4ω in a measurable amount. To solve this problem, a set of optics were used in the laser front end to down collimate the regenerative amplifier light into a pencil beam of $\sim 1/8$ " in diameter. Using this beam, the signal from the PMT was of the order of 200 mV, more than enough to tune the crystal. This also allowed for a $1/2$ " diameter wave plate to be inserted into the beam line near the crystal to ensure the light in the PMT tube was from 4ω and not the

2ω light from the beam line by rotating the polarization. As an alternative approach, a Coherent model xxx laser was injected into the 4ω crystal and its conversion was measured. While this approach appears to work, there is some concern that the angle at which the Coherent laser passes through the crystal will not match that of the main laser system, although the retro-reflected light from the coherent laser was matched to the retro-reflection of the CW alignment beam used to align the main laser pulsed beam.

After initial crystal alignment, a rocking curve for the crystal was also obtained using low level rod shots with ~ 700 mJ of energy. The curve shows the correlation between the energy lost in the frequency doubled 2ω light from the first conversion crystal with the gain in 4ω from the second conversion crystal as a function of crystal angle Figure 2a. The FWHM of the tuning is approximately ~ 2.4 mRad. This is consistent with other measurements of this type of crystal for conversion to the forth harmonic. The Figure 3a shows the output energy of the 4ω Thomson scattering system as a function of the incident 1ω input energy. The data show energies of up to 15 J have been achieved. The conversion efficiency of the system as is shown in Figure 3b. The conversion efficiency increases with increasing power as expected. However, there is some variability in the system as indicated by the data.

IV. 4ω Thomson Scattering Diagnostic

The 4ω Thomson scattering diagnostic consists of a low resolution spectrometer system for measuring scattering from electron-plasma fluctuations and a high resolution system to measure scattering from ion-acoustic fluctuations. The output of either spectrometer can be coupled to a streak camera for a temporally resolved measurement or a gated CCD camera for spatially resolved measurements. An example ion-acoustic wave spectrum from a CH foil target is shown in Fig. (4) and compared to a calculated Thomson scattering form factor. Future

experiments will heat this target with the Titan short pulse beam allowing heat flux measurements behind the critical surface.

IV. Conclusions

A 4w Thomson scattering probe beam has been build for use at the Titan laser facility. The system has demonstrated good performance with up to 15 Joules in 4w light. The new capability adds the potential for measurements of plasma conditions on future experiments while opening up the possibility of novel experiments for the facility. The Thomson scattering arrangement also can be used to generate probes at other frequencies as well.

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Captions

Figure 1: Schematic diagram of system layout.

Figure 2: Map of rocking curve showing both (●) 4w and (□)2w unconverted light. The dashed curve represents a Gaussian set to match the 4w data.

Figure 3: a) 4w output energy versus the 1w input energy for the Thomson scattering probe beam and the associated (b) conversion efficiency

Figure 4: Thomson scattering from ion-acoustic waves is compared to the calculated Thomson scattering form factor for an electron temperature of 650 eV and a scattering parameter of 1.0







